TWO-CENTIMETER GPS MEASUREMENT SYSTEM FOR MISSILE INTERCEPT T&E

T. Thompson
L. J. Levy
J. M. Dougherty
T. M. Hattox
The Johns Hopkins University
Applied Physics Laboratory
Laurel, Maryland

Abstract

Accurate scoring (miss or impact measurement) of missile intercept tests is required to adequately assess lethality. Instrumentation approaches based on a suite of sensors (e.g., Doppler radar Miss Distance Indicator, optical fiber Photonic Hit Indicator, and ground radar tracking) are not capable of meeting the full range of requirements. On the other hand, our long experience with Trident missile system accuracy evaluation and early BMD intercept testing suggests that dual frequency wide-band (P-code) *GPS translators* on the interceptor and target can meet missile intercept test requirements. This paper describes the GPS system configuration required and presents experimental results to demonstrate two centimeter accuracy in a very high dynamic missile intercept type environment.

Introduction

In support of the Navy's Trident programs, The Johns Hopkins University - Applied Physics Laboratory (JHU/APL) has been applying post-flight GPS signal tracking techniques since 1978.[1,2,3] The techniques, developed at JHU/APL, are used to provide precision trajectory measurements for post-flight evaluation of Trident missile test flights. A GPS translator on the test missile receives GPS signals and converts the signals to S-band for retransmission to the missile telemetry station. The telemetry station receives the translated GPS signals, amplifies, down-converts, digitally samples, and then records the data for post-flight playback. A special facility, at JHU/APL, is used to track the GPS signals during post-flight playback of the recorded data. The system, known as *SATRACK*, was operational for the Trident I system in 1978 with a major upgrade for the Trident II system in 1987.[4,5,6] The current capability, designed to support the Navy's Extended Navy Test Bed (ENTB) program, provides post-flight receiver operations for the complete GPS signal (i.e., full P(Y) code modulation for both navigation frequencies). Translators (versus receivers) are the preferred instrumentation. They are simpler than receivers and they require no initialization process (i.e., a translator is a simple radio relay, receiving signals at one frequency and re-transmitting them at another frequency).

In 1991-92, JHU/APL adapted SATRACK to process GPS data from the Exoatmospheric Reentry Vehicle Interceptor Subsystem (ERIS) flight tests. Although the instrumentation was restricted to single frequency narrow band C/A-code transmissions, it provided 60 cm measurement uncertainties in the two intercept flight tests conducted for the ERIS program.[7] One of the two tests had a successful intercept. The GPS measurement results were more precise, and yet, statistically consistent with all other available observations. The measurement system provided a full geometric description of the intercept and miss event for the two flights. Additionally, the ERIS translator measurements successfully provided interceptor guidance and seeker performance evaluation capabilities.

Considerations of the eventual need for a more precise measurement capability led us to evaluate whether the ERIS system could be improved. Our studies and analysis led us to the conclusion that GPS could do this job using full (i.e., dual frequency wideband) GPS signals. It had already been demonstrated that millimeter precision was possible between stationary GPS antennas through the application of differential carrier phase ranging techniques. In more recent times this technique has been demonstrated in low dynamic applications.[8] The real question was whether this technique could be applied to the high dynamic short time span measurements characteristic of missile intercepts. Based on our ERIS experience and subsequent test and analysis work[9], we were confident that the technique could be applied to this application, however, we recognized that a representative demonstration would be required to validate this conclusion. We first proposed

this measurement approach and demonstration project in 1993. However, there was no opportunity to go forward prior to completion of the ENTB program.

In 1994, there was a need for full signal translators for the ENTB program. The translator and special receiver/recording equipment needed to record the wide bandwidth signals were developed at JHU/APL. This system was successfully used with two reentry bodies during a Trident flight test in December 1995. The Navy allowed us to use some of the equipment designed for ENTB to conduct a special JHU/APL IR&D test project to demonstrate the proposed intercept measurement concept. The remainder of this paper will describe the intercept measurement methodology, the demonstration test configuration, and the results of the demonstration.

Intercept Measurement Approach

The Basic GPS measurement concept is shown in Figure 1. In simple terms, radio frequency signal paths (*links*) are used to determine time-of-arrival of code modulated signals from multiple GPS satellites and Doppler frequency shifts along those links. If GPS time were known on the missile, each time-of-arrival measurement could be used to calculate the distance (*range*) to each satellite. Range to each satellite combined with satellite locations defines the position of the missile. Actually, in this circumstance, missile position could be determined with only three satellites. Four satellite measurements (*pseudo ranges*) are used to compute the three components of missile position and an offset from GPS time. In our approach no signal processing is required on the missile; a translator rebroadcasts the GPS signal for ground processing.

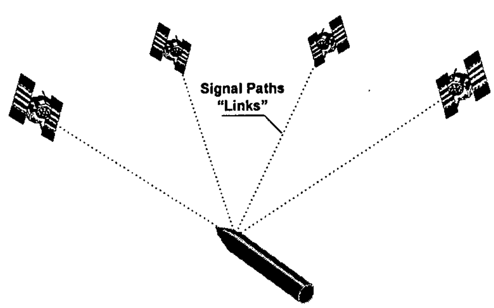

Figure 1. Basic GPS Measurement Concept.

Time-of-arrival measurements are obtained by observing the arrival time of a particular transition (*phase*) of a code signal applied as phase modulation to each satellite transmission. Doppler characteristics are usually measured by integrating the frequency output of a phase-locked loop tracking the GPS carrier signals. With frequency errors removed, integrated Doppler provides a precise measure of the range change over the period of integration. Together these measurements are used to compute position and velocity of the missile.

GPS Signal Structures

Satellite signals are transmitted at two frequencies: L_1 - (1575.42 MHz), and L_2 - (1227.60 MHz). Signal data at the two frequencies are used to compute corrections for time delays resulting from refraction as the signals pass through the ionosphere. Both frequencies are modulated with message data at a low rate (50Hz) and a biphase ranging code (clocked at 10.23MHz). This code modulation, referred to as the Precision- (or Protected-) code or P-code, is encrypted so that it can only be received by authorized users. A second biphase ranging code (clocked at 1.023MHz) is applied to the L_1 transmission only. This code is not encrypted and is more easily acquired, it is referred to as the Clear/Acquisition-code (C/A-code).

Intercept Measurements

JHU/APL proposed and implemented an adaptation of SATRACK for ERIS intercept measurements. Two intercept tests were conducted: the first, on 28 January 1991, ended with a direct hit; and the second, on 13 March 1992, was a near miss. Figure 2 shows the ERIS test configuration.

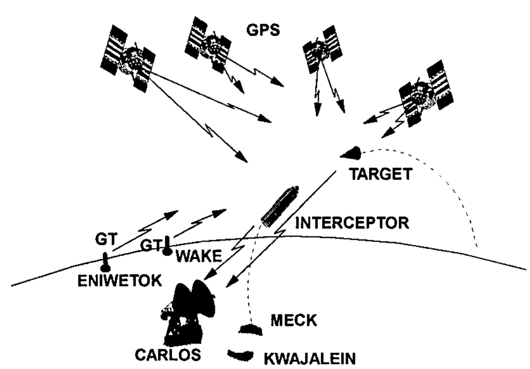

Figure 2. ERIS Test Configuration.

In this configuration, GPS signals are translated from both the target and the interceptor. Additional satellite-like ground-based transmitters were also used to improve the tracking geometry. Trajectories for each vehicle were obtained by the same kind of post

processing used for Trident missiles. Absolute trajectory uncertainties of 2 meter position and less than 1 cm/sec velocity were achieved. But beyond that, a differential GPS solution was used to define the relative position vector to an accuracy of less than 60 cm.

The differential processing used to determine the ERIS miss/impact geometry is based on a relative measurement between the two trajectories. In this case, the relative position measurement is more important than knowledge of absolute positions of the individual vehicles, and uncertainties in the absolute positions of each body are larger than the uncertainties in the relative position vector. The condition is illustrated in Figure 3.

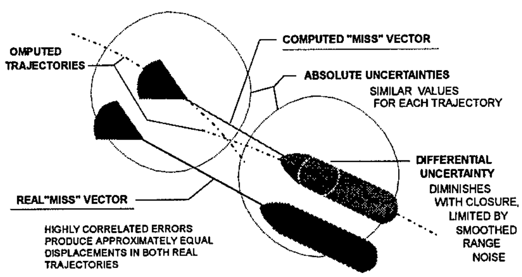

Figure 3. Relative Measurement Concept.

The absolute trajectories of both vehicles have many common (i.e., correlated) errors. Satellite ephemeris and clock errors produce nearly the same absolute error in both trajectories and the ionospheric errors are nearly identical when the vehicles are almost at the same location. In the limit, the only error remaining in defining the miss geometry (measured relative to the two vehicle antenna phase center locations) is the range noise. Antenna design considerations become quite important to achieving the highest precision measurements.

Carrier Cycle Ranging

The ERIS tests used L_1 C/A-code pseudo-range and carrier phase data. The range noise was smoothed by taking advantage of the low noise inherent in using phase data to determine range changes between independent range measurements. Since carrier phase measurements are based on observations of carrier cycles, the apparent range noise in a range change measurement is a fraction of the signal frequency wavelength (i.e., a small fraction of 19 centimeters). By way of contrast, the range measurement noise typical of the C/A-code data, in a 1 Hz bandwidth range tracker (i.e., one sample per second), is nearly 5 meters. Under equivalent signal conditions, P-code range noise would be less than 65 cm. Contiguous carrier phase data samples can be used to combine range data samples to reduce the range noise by the inverse of the square root of the number of samples combined (e.g., contiguous data combined over a 100 second interval would reduce the above C/A-code range noise by a factor of 10, to 50 cm).

While carrier cycle range noise is small, it is not normally useful as derived range measurements because it is completely ambiguous at the signal wavelength level (i.e., the range is known to within a fraction of 19 cm, but how many cycles there are between a satellite and the user antenna is unknown). Absolute measurements are not possible at this precision because the satellite locations and signal propagation effects are not known well enough to work out the ambiguities. However, these techniques can be successfully applied to relative measurements.

A particular satellite-to-satellite range difference defines a hyperbolic surface containing the tracked vehicle's antenna. Three such surfaces (four independent satellite differences) locate the vehicle. If the ranges are derived from carrier cycle ranging, the single surfaces are replaced by a series of concentric surfaces separated by a wavelength. The differential (miss geometry) measurement is based on a computation that uses second differences (i.e., the difference between identical satellite-to-satellite differences as measured at the two vehicles). Each double difference carrier phase measurement will produce multiple surfaces of revolution, each separated by one wavelength. Carrier phase noise will cause each surface to be slightly fuzzy.

The true relative position vector must end where all surfaces intersect at a common point. Finding this point would be easy if the differential position uncertainty from carrier phase smoothing of range were small enough or the surface fuzziness due to carrier phase noise were zero! In the real case, a search technique is used to examine all possible combinations of integers in an allowable search sphere surrounding the computed/estimated relative position vector from carrier phase smoothing. The ambiguity combination yielding the smallest fitting residuals is the chosen solution, and the uncertainty is equal to a small fraction of the carrier wavelength. This process requires a minimum of one additional in-view satellite (i.e., a minimum of five satellites, or satellites and ground transmitters, are required).

The ambiguity search is greatly simplified when both GPS signals (L_1 and L_2) are processed. Wide-laning and narrow-laning techniques use tracking data from the two GPS frequencies to create computational wavelengths that are equal to the difference and sum frequencies (i.e., 86 cm and 10.9 cm). When this technique is combined with the range noise performance available from P-code tracking, ambiguity resolution is very strong; this will clearly be seen below, where the demonstration data processing is discussed. Furthermore, the two frequencies provide redundant independent solutions, which increase the likelihood of success. Although the dual frequency capability may not be required to overcome ionospheric errors in this measurement, robustness of the dual frequency technique strongly supports the dual frequency P-code configuration.

Some have raised concerns with regard to the bandwidth required to translate the full GPS signal spectrum. When translator bandwidth is compared to telemetry bandwidth requirements, it may appear to be excessive. However, when compared to alternative *tracking* techniques, radar for instance, the translator spectrum is quite modest. Furthermore, in spite of its bandwidth, the transmit power requirements are usually no greater than that of typical missile telemetry transmitters. The ENTB design clearly demonstrates the practicality of wideband translators.

Accurate impact analysis also depends on a comprehensive description of the velocity and attitudes of the two bodies at the time of impact. Measurement of the relative velocity of the two bodies is a straightforward extension of the GPS technique used for measuring relative position (i.e., velocity is observed in the differential GPS phase rate data). Attitude measurements require additional information. In many instances, the target and interceptor have independent means for sensing attitude. As long as the attitude sensor data is telemetered, the attitude histories of both bodies can be reconstructed from that data. In many cases, where the attitude accuracy is limited by the available sensor, GPS can be used to greatly refine attitude measurement precision, by analytically combining the two measurement sources.

Independent attitude measurements from GPS signals are possible with a multiple antenna configuration. Measurements of phase differences received at two antennas indicate the angle to the signal source relative to a line defined by joining the two receiving antennas. Three antennas can provide sufficient measurements to determine body attitude. Attitude precision is inversely proportional to the distance between antennas. Although there are ambiguities in the measurements, redundancies provided by the multiplicity of signal sources are sufficient to remove them. While multiple independent GPS receive antennas might not be justified for additional attitude information, the need to provide full angle viewing and to precisely define antenna phase center locations to a fraction of a centimeter may together justify such a configuration. Application of multiple independent antenna position-tracking techniques also favors a translator instrumentation configuration.

All of the techniques required to achieve centimeter level measurements have been demonstrated within the Navy's ENTB program. However there were no means within that program to experimentally verify the instrumentation's relative positioning precision. The demonstration discussed next has now provided that verification.

Concept Demonstration

The concept demonstration was conducted at the Holloman AFB High Speed Test Track on August 8 and 9, 1996. The test included two GPS translator equipped bodies, one rocket propelled on a monorail and the other stationary. The dynamic sled consisted of an instrumentation section attached to a 9-inch diameter Pupfish rocket with a ZUNI pusher using a stack of 7 rockets, as shown in Figure 4. The dynamic sled was propelled along rail #1 of the test track. The stationary sled consisted of a duplicate instrumentation section clamped to the second rail of the test track. Both instrumentation sections used the same type GPS antenna designed specifically for conformal mounting on the test bodies. The dynamic body used an S-band blade antenna to relay the translated GPS signals to the antenna at the Track Data Center (TDC). A second blade antenna transmitted the body telemetry signals. S-band signals from the stationary body were carried by cable to the track-side blockhouse. Translated GPS signals were recorded at both sites using ENTB receiver/recording equipment.

Image Motion Compensation (IMC) cameras were positioned to capture the dynamic body image as it passed through the point of closest approach. The camera data combined with other measurements provide an accurate independent measure of the distance between the two GPS antennas at the point of closest approach.

Figure 4. Rocket sled ready for launch.

The day before the rocket sled test, a slow speed tow test was conducted where the dynamic instrumentation body was pulled past the stationary body. Translated GPS signal data were recorded at both stations to provide for test calibration and to examine S-band multipath between the dynamic sled and the TDC. Figure 5 shows the two instrumentation bodies near closest approach as they appeared during the tow test.

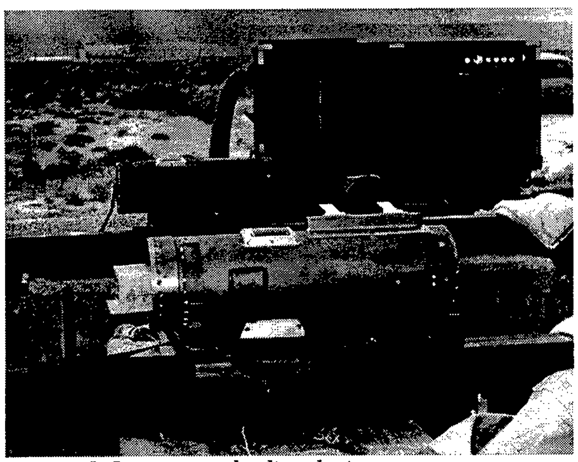

Figure 5. Instrument bodies during tow test.

GPS Instrumentation

Each instrumentation body had the same specially designed GPS antenna, the same type low noise preamplifier, and equivalent translators. The dynamic translator power output of 5 watts* connected directly to a blade antenna. The stationary translator output, with its power amplifier stage bypassed, was connected by cable to the receiver/recorder equipment in the blockhouse. The cable run was about 700 feet and there was one boost amplifier midway through the cable run.

With regard to GPS signals the translator functions as a mixer and amplifier. In this particular design, the first local oscillator is set between the two GPS frequencies, and the first mixer output overlays the two signal spectra. This was done to minimize the S-band bandwidth needed to translate the GPS signals. The translator output also includes an S-band *pilot carrier* (i.e., a tone) that is produced as a direct multiple of the translator oscillator used to synthesize the local oscillator tones that produce the translated GPS signals. Phase locked tracking of the pilot carrier signal is used to aid tracking of the GPS signals. This technique removes translator oscillator effects from the GPS post-flight tracking operations.

The receiver/recorder equipment designed for the ENTB program needed to be portable, and it is simply designated as Portable Ground Equipment (PGE). A single PGE is designed to receive two translator S-band signals (two polarizations), convert the received signals to near baseband, coherently sample the baseband signals, and record the signal samples. A PGE also includes a GPS signal simulator and real-time GPS signal tracker capability for self test. This equipment is more completely described in a recent ION paper.[10]

The PGE's GPS tracker is limited, but it was useful in this test setup for real-time tracking of a single satellite whenever the stationary translator was operating, or when the dynamic translator was operating and stationary. The track configuration included four PGEs for redundancy. Two units were at the blockhouse receiving the stationary translator signals from the cable run and two were at the TDC receiving signals from the dynamic translator via the TDC antenna and S-band preamplifier network.

The data recorded by the PGEs during all test operations were played back at the Trident post-flight tracking facility. Tracking data from the facility were then used to reconstruct the *intercept* geometry of the test using carrier cycle ranging techniques.

Initial carrier cycle integers were determined from signal data taken over the 60 second interval preceding launch. At the distance between the two bodies, prior to launch (~1880 m), propagation differences in troposphere and ionosphere were not a factor. Signal data were combined with DMA precision ephemeris to position the static sled. GPS tracked data were then double differenced (i.e., satellite-to-satellite and body-to-body) to estimate wide-lane integers every second.

Next a time history of the narrow-lane integers were estimated using only double differenced phase data. This initial solution is used to compute refined estimates that remove nonlinear propagation and timing

* Five watts is the normal ENTB power level, it was not required for this test.

errors. These in turn allow determination of the L_1 and L_2 integers through an ambiguity search.

The high dynamics were expected to produce cycle slips in the tracking loop outputs. However, iterative tracking techniques allowed these to be minimized to an extent that proper corrections could be made. Integer multiples of half cycle slips were expected and they were easily detected at relatively few points in any link. Application of the narrow-lane process with the high quality tracking data provided direct evaluation of shifts to allowable quantized values which in turn exactly established the magnitude of carrier cycle slips needed to restore the integrity of continuous phase measurements throughout the powered flight. The quality in the final corrected links is evident by examination of the double differenced phase measurements and the relative best estimate of trajectory over the flight path. Over all the six tracked satellites, these residuals have, for L_1, a mean of 1 mm and a standard deviation of 6 mm, and for L_2, a mean of 4 mm and a standard deviation of 8 mm. Because the two frequencies provide independent solutions, the final estimates were based on a solution using both. Trajectory accuracy results will be described more fully in a later section.

Special Track Instrumentation

The track is equipped with a location measurement system based on magnetic interrupters. Time-of-day is recorded as the sled passes each interrupter. The accuracy of this system, known as *Spots*, is limited by uncertainties in the exact position and timing of the interrupt. Higher precision, in the region of closest approach, was provided by some additional instrumentation, discussed below. The precision cameras, noted above, provided a single point measurement to sense movement of the dynamic GPS antenna in relation to the track surface and center-line. One of the two pictures provided by the camera system is shown in Figure 6. The picture was taken at a sled speed of 1,372 meters/second.

In addition, a precision fiber optic system was used to accurately measure the time-of-closest-approach and the time at three positions on either side of that point. Position errors relative to the point-of-closest-approach for the system are accurate to a small fraction of an inch. The absolute time of any break is accurate to less than 2 microseconds and the relative time between events is accurate to less than 200 nanoseconds. A similarly configured, but less accurate, break-wire system was included as a backup to the fiber optic system. Together these systems provide a survey accuracy in the region of closest approach that is less than one centimeter.

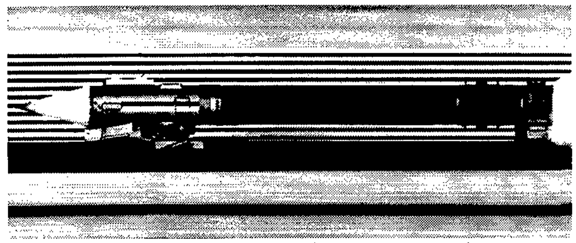

Figure 6. Dynamic sled at closest approach.

It may be suggested that the peak velocity of this demonstration is not representative of some missile intercept tests. However, it must be noted that constant velocity (at any magnitude) is no challenge to phase-locked loop tracking. A second order loop will track a constant velocity with no error; after all, orbiting satellites are easily tracked even though they have very high velocities. The true challenge for signal tracking is related to changes in velocity (i.e., acceleration and its derivatives). In that regard, this demonstration includes excessive dynamics as related to all intercept tests of which we are aware.

Demonstration Dynamics

The need to provide a high speed intercept-like test condition in a limited yet well controlled trajectory space, led to selection of the Holloman high speed test track. The high dynamic conditions as derived from an on-board accelerometer are shown in Figure 7.

In many ways the test track environment is more stressful than most (maybe all) real missile intercept conditions. In our case, the test body exceeded mach 4 in about one mile of travel. This required very high acceleration. Being held captive to the track with high acceleration produces rather large vibration accelerations in cross-track and along-track directions. Finally during each ignition and cutoff event, jerk levels from 300 to 1500 g/s were experienced. In order to exercise the GPS tracking system at or near the highest velocity point, one of the higher jerk conditions occurred at the point-of-closest-approach. The ability to operate a phase-locked loop through these very demanding conditions is a prime reason for recommending translators for intercept instrumentation. Since all phase-locked loop tracking is accomplished post-flight through playback of recorded signal data, the process can be iterated as often as necessary. Signal translation, broadband signal sampling, and recording are very much simpler and more robust processes than that required for operating receivers in this type of

environment. Recognizing the substantial investment associated with missile intercept testing, it seems imperative that translator instrumentation be used for this purpose.

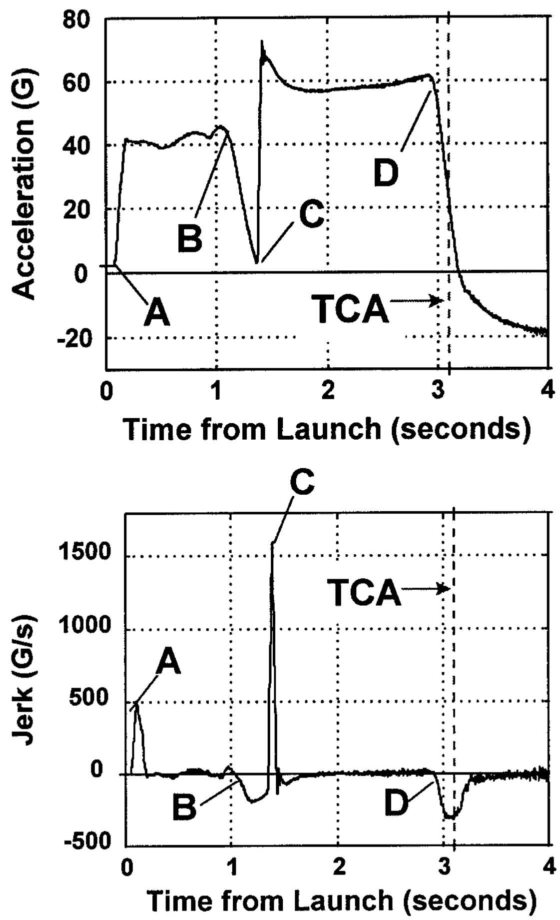

Figure 7. Sled acceleration and jerk profiles in high dynamic region; A= first stage ignition; B= first stage cutoff; C= second stage ignition; D= second stage cutoff. Time-of-Closest-Approach (TCA) is also shown.

Demonstration Test Results

Before considering the miss geometry evaluation, it is instructive to look at the GPS measurement of acceleration in the high dynamic region. Figure 8 shows the acceleration profile as determined from GPS signal processing (i.e., a pure GPS-only measurement); it should be compared with the accelerometer measurement shown in figure 7. Since the GPS measurement is restricted to ten measurements per second it will not follow the higher frequency components, but apart from that characteristic, it provides an excellent measure of the sled dynamics.

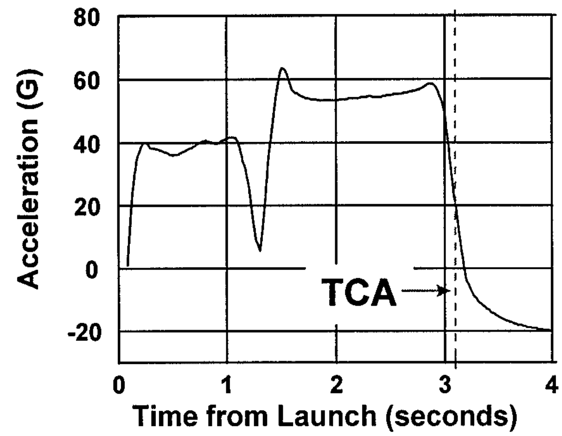

Figure 8. GPS-derived acceleration profile.

The remainder of this discussion will focus on the measurement of miss geometry. Figure 9 shows the basic geometry and defines the coordinate system for our measurements. Relative position vector measurements are defined in terms of *(along-track, cross-track, vertical)* components. The origin is on the surface of the track directly below the center of the stationary body GPS antenna. The along-track direction is aligned to the nominal direction of the track and set to be parallel with the local tangent at the stationary body track station, with positive in the direction of travel. Vertical is positive up, and the cross-track is positive toward the other rail. The vector at closest approach is (0, 2.133, 0) meters.

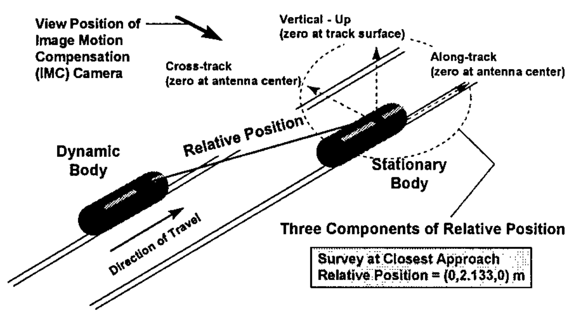

Figure 9. Relative position vector geometry.

The GPS cross-track position estimates relative to the survey position (with rail separation removed) are shown in Figure 10, for L_1 and L_2 frequencies. An *error* can only be estimated at the point of closest approach. However, if the rails were perfectly straight and our coordinate frame perfectly aligned with the track, the cross-track component of the relative position vector would be constant (i.e., equal to the survey measurement at closest approach - represented as zero in the figure).

If these measurements had a single slope, it could be removed by a slight rotation of our coordinate system; but, there is a break point within the data span. The most significant point to be made regarding this data, is that we are looking at a few centimeter variation over a track span of more than 10,000 meters! The GPS measurement of relative cross-track position in the survey region is shown in Figure 11. Here the data from both signal tracks was combined to provide the maximum GPS measurement accuracy.

Relative vertical position estimated over the full measurement span are shown in Figure 12 for both frequencies. Again, as with the cross-track data, accuracy can only be assessed at closest approach. Track variations in the vertical direction were expected. The high point at closest approach is due to setting our coordinate system tangent to the track surface at that point.

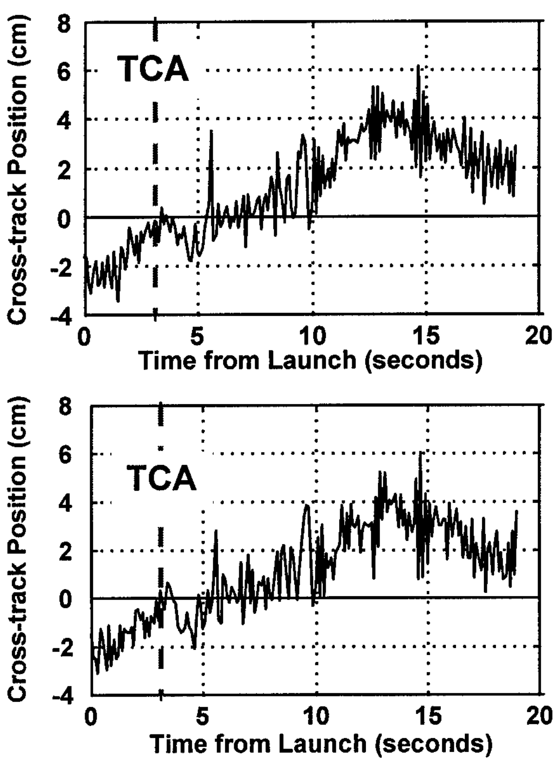

Figure 10. Cross-track measurements made with the two GPS signal frequencies; top plot is based on L_1 signal tracking, bottom plot is based on L_2 signal tracking.

The vertical difference between the GPS measurements and survey in the region near closest approach is shown in Figure 13.

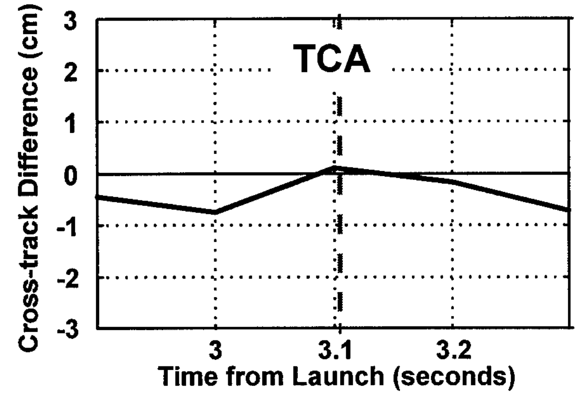

Figure 11. Cross-track difference (GPS-Survey).

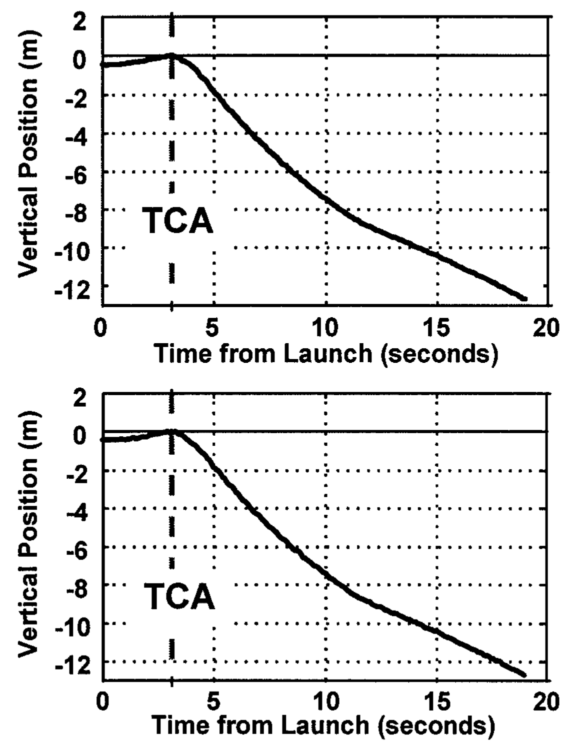

Figure 12. Vertical measurements made with the two GPS signal frequencies; top plot is based on L_1 signal tracking, bottom plot is based on L_2 signal tracking.

Figure 14 shows the along-track relative position measurement as determined from GPS signal tracking. Time-of-closest-approach is derived from this data by simply observing the time when the position passes through zero. An error can only be introduced by our inability to accurately identify the time-of-closest-approach. The distance span of this data is seen to be greater than 10,000 meters; with the launch point at about -2,000 meters and the end point beyond 8,000 meters.

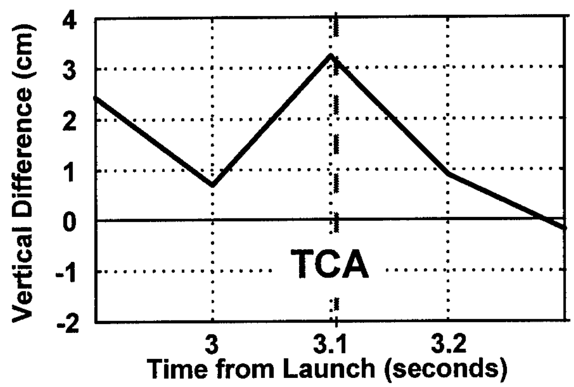

Figure 13. Vertical difference (GPS-Survey).

Figure 15 shows a plot of the seven data points provided by the fiber optic system. It covers a distance span of 31.693 meters centered on closest approach. Fibers were stretched across the track at seven surveyed locations. The central fiber was positioned to break at the point where the two GPS antennas were at closest approach. The fiber optic cable system provides an independent time/position measurement at the seven surveyed locations for direct comparison to the GPS-derived position measurements.

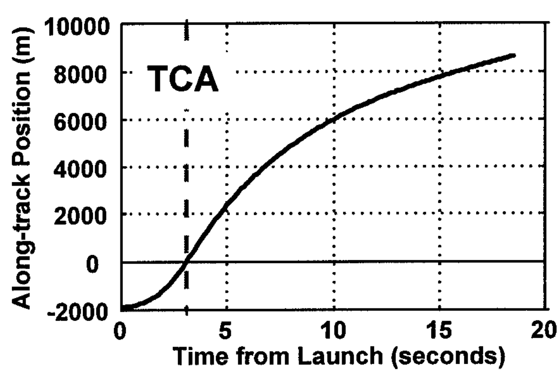

Figure 14. Relative along-track position from GPS.

Determination of along-track difference is based on the comparison of GPS relative along-track position with the fiber optic cable break measurements. Figure 16 shows that comparison.

The difference in the observed relative position vector between surveyed and GPS measurements are summarized in Table 1. These smoothed results were determined from straight-line fitting the near-TCA differences shown in Figures 11, 13, and 16. The survey measurements combined with fiber optic and camera processing uncertainties are assessed to produce less than one centimeter error in the reference position used for comparison with the GPS data. The uncertainties shown in the table are those associated with the GPS measurement process. The differences can only be considered relative position errors if the surveyed data is assumed to be errorless. In any event, the differences between the reference and GPS measurements are seen to be less than two centimeters in all coordinates, with the maximum difference in the vertical measurement. The data clearly verify that a translator-based GPS relative measurement system can provide two centimeter accuracy in a high dynamic environment.

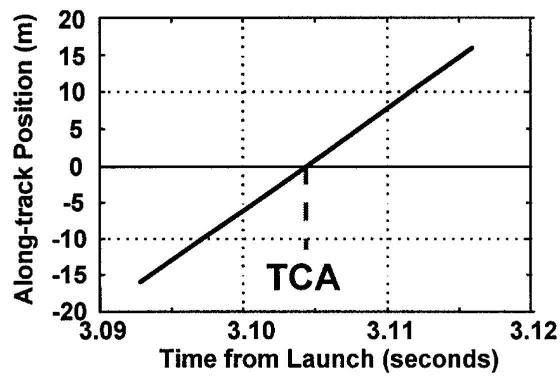

Figure 15. Along-track position from fiber optics.

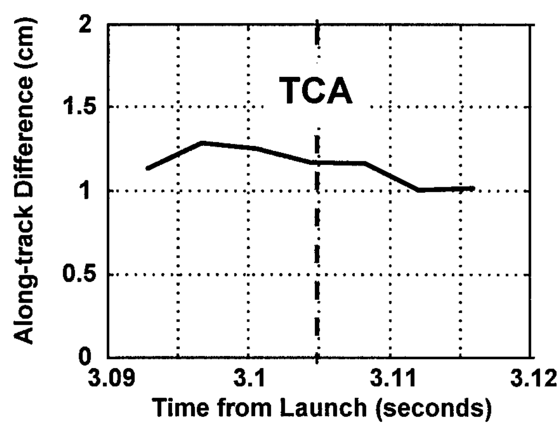

Figure 16. Along-track difference (GPS-Survey).

Conclusion

We have been convinced, based on analysis and experience with GPS Translator-based precision missile tracking, that this technique could achieve two-centimeter measurement precision in a missile intercept flight test environment. The virtues of GPS measurements for this application are compelling. With GPS, a single instrumentation system can provide guidance evaluation capability, as it has with Trident

since 1978. It can provide range safety tracking support, as it has with Trident since 1987. It can provide miss/impact measurements and seeker evaluation capability, as it did with ERIS in 1991. Now the test at Holloman's High Speed Test Track has clearly demonstrated that this technique can also support lethality evaluations. We know of no other system that can provide all these capabilities. Furthermore, GPS is truly global; it will provide these capabilities at all test ranges. Finally, we should emphasize that only translator-based GPS instrumentation provides a low risk approach to achieving the precision intercept measurements required to support the most demanding lethality evaluation test conditions.

Acknowledgments

We are most grateful for the support and cooperation we have received from the Navy's Strategic Systems Programs organization in making this paper possible. Their leadership throughout the evolution of this technology and the specific impetus provided by the ENTB program provided the foundation for this work. We are especially thankful, in this regard, for the encouragement provided by Mr. M. Meserole. We also wish to acknowledge the special work of the APL test team at Holloman: Mr. G. T. Moore, Mr. J. Brown, and Mr. T. French. And we are grateful for the excellent support provided by the Holloman track team, especially the efforts of Second Lieutenant D. Roland in coordinating test activities. We are also grateful to those who provided support in doing the post-tracking and analysis operations: Mr. M. Feen, Mr. S. Lim, and Mr. S. Bergmann.

Table 1
Relative Position Difference (GPS-Survey)

Component	Difference (cm)	Uncertainty (cm)
Along-track	1.1	0.8
Cross-track	-.03	0.6
Vertical	1.4	1.8

References

[1] Thompson, T., "Performance of the SATRACK /Global Positioning System Trident I Missile Tracking System," *IEEE Position Location and Navigation Symposium* (1980).

[2] Vetter, J. R., Schwenk, V. L., and Hattox, T. M., "Ballistic Missile Trajectory Reconstruction and Error Estimation from a Satellite-Based Tracking System (SATRACK) of Operational Trident I Flight Tests," *Eighth Biennial Guidance Test Symposium* (1983).

[3] Westerfield, E. E., "The Use of Translators with GPS," *International Telemetry Conference* (1984).

[4] Levy, L. J., "Requirements Study for a Trident II Accuracy Evaluation System," *APL Developments in Science and Technology*, JHU/APL DST-10 (1982).

[5] Duven, D. J., Meyrick, C. W., Vetter, J. R., and Feen, M. M., "Performance Experience of and Design Goals for the SATRACK I & II Missile Tracking Systems," *Proceedings of the First International Symposium on Positioning with GPS* (1985)

[6] Vetter, J. R., Schwenk, V. L., and Hattox, T. M., "An Improved GPS Based Tracking System for High Accuracy Trident II Missile Navigation and Guidance Evaluation," *Fourteenth Biennial Guidance Test Symposium* (1989).

[7] Hattox, T. M., Westerfield, E. E., and McNellis, J. R., "Precision Determination of Trajectory and Miss Distance of ERIS Interceptor and Target (U)," SECRET, *AIAA Missile Sciences Conference (Proceedings)*, Monterey, CA, February 1993.

[8] Evens, A. G., Hermann, B. R., Remondi, B. W., Simpson P. B., Feist, J. L., Wiles, G. C., "An Evaluation of Precise Kinematic On-The-Fly Relative GPS Positioning for a Rocket Sled Test," *Proceedings of the 52nd Annual Meeting of the ION* (1996)

[9] Levy, L. J., Hattox, T. M., and Hohman, D. S., "GPS Tuned Ephemeris Demonstration for Precision Strike (U)," SECRET/NOFORN, *AIAA Missile Sciences Conference (Proceedings)*, Monterey, CA, November 1994.

[10] Thompson, T., Levy, L. J., Dougherty, J. M., Hattox, T. M., "Collection and Analysis of GPS "Raw Data" for Multipath Modeling and Receiver Testing," *Proceedings of the 52nd Annual Meeting of the ION* (1996)

OFFICE OF THE UNDER SECRETARY OF DEFENSE (ACQUISITION & TECHNOLOGY)
DEFENSE TECHNICAL INFORMATION CENTER
CAMERON STATION
ALEXANDRIA, VIRGINIA 22304-6145

IN REPLY REFER TO DTIC-OCP (703) 274-6847 (DSN) 284-6847
AQ

SUBJECT: Request for Scientific and Technical Report

TO:

1. We have been unable to locate the report referenced below in the Defense Technical Information Center Collection. In accordance with DoDD 3200.12 "DoD Scientific and Technical Information Program" the Defense Technical Information Center is to receive two copies of the Technical Report cited below.

2. All copies of the report must be suitable for reproduction including a clearly marked distribution statement as described in DoDD 5230.24. (See reverse side for categories of distribution statement.) A clearly marked loan copy suitable for reproduction is acceptable.

3. If for any reason you cannot furnish the report, please return the copy of this letter annotating your reason on the reverse side.

4. A mailing label for shipping the reports and a DTIC Form 50 to obtain the AD number after processing are enclosed.

2 Encl
1. Mailing Label
2. DTIC Form 50

Chief, Programs
Management Branch